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SUMMARY OF A WORKSHOP ON PLANT CANOPY STRUCTURE, 27-30 APRIL 19--ETC(U)
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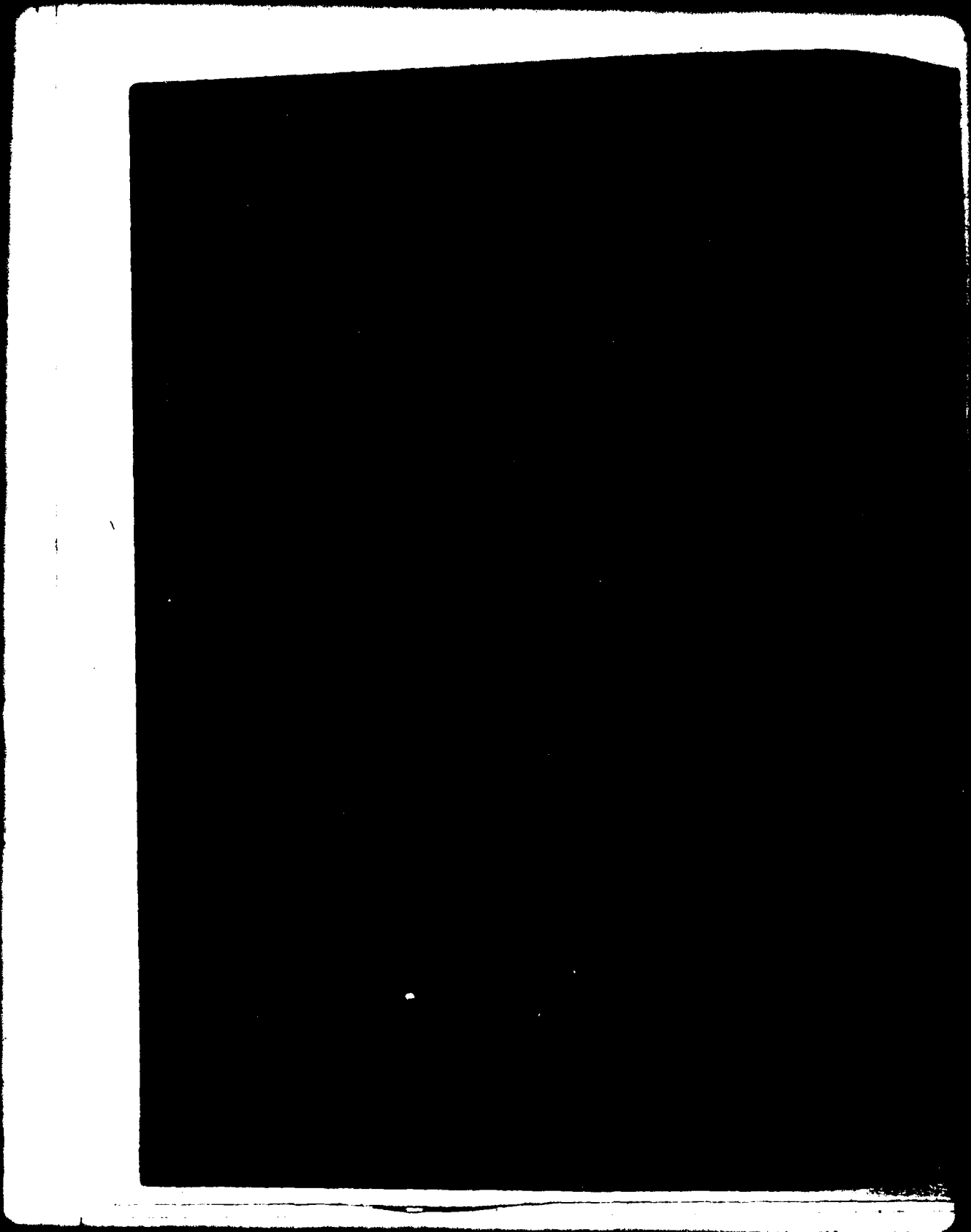
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20. ABSTRACT (Continued).

its effects on rates of transport and diffusion of atmospheric materials or its interactions with electromagnetic radiation.)

During the period of 27-30 April 1981, a Workshop on Plant Canopy Structure was held at Oak Ridge, Tenn. Over 30 individuals representing a broad range of disciplines and specific areas of expertise were in attendance. Primary objectives of the workshop were to: (a) define needs for and applications of quantitative canopy structure information, (b) assess the state of the art of canopy structure measurement techniques, (c) define and assess needs for further research, and (d) stimulate and focus new research efforts. A summary of the workshop, in terms of these objectives, is presented; recommendations for future efforts in plant canopy structure research are also given.

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PREFACE

The workshop on plant canopy structure was planned and proposed by a steering committee consisting of Dr. Lee K. Balick, Colorado State University, on assignment to the U. S. Army Engineer Waterways Experiment Station (WES); Dr. Boyd A. Hutchison, Atmospheric Turbulence and Diffusion Laboratory; Dr. Lloyd Gay, University of Arizona; Dr. John Norman, University of Nebraska; and Dr. James Smith, Colorado State University. The workshop was sponsored by the Army Research Office with additional support provided by WES and the Oak Ridge National Laboratory.

Technical monitor for the workshop was Dr. Steven J. Mock, Army Research Office. The workshop was administered and hosted by Science Applications, Incorporated (SAI), in Oak Ridge, Tenn. Principal Investigator for SAI was Ms. Carole Shriner. SAI Conference Coordinator was Ms. Judy Mason. This report was published by WES under Department of the Army Project No. 4A762730AT42, Task A4, Terrain/Operations Simulation, Work Unit 003, Electromagnetic Target Surround Characteristics in Natural Terrains, which is directed by the Environmental Constraints Group, Environmental Systems Division, Environmental Laboratory, at WES. The report was edited by Drs. Balick and Hutchison.

Commander and Director of WES during publication of this report was COL Tilford C. Creel, CE; Technical Director was Mr. F. R. Brown.

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SUMMARY OF WORKSHOP ON PLANT CANOPY STRUCTURE

PART I: INTRODUCTION

1. Interactions among structural features of plant canopies, physical environmental factors, and the physiological functioning of plant stands critically impact a diverse array of contemporary environmental issues of society. For example, the interactions among electromagnetic radiation, canopy structure, and primary productivity are of importance (1) to agronomists and foresters concerned with maximizing crop yields, (2) to ecologists concerned with the energy implications of ecosystem structure and function, and (3) to scientists and technicians concerned with remote assessments of large-scale crop status and yield. Similarly, these interactions are of importance to meteorologists concerned with surface effects on atmospheric processes, especially the diffusion, transport, and deposition of materials carried by the atmosphere. Military interests arise because of the obscuration of targets by vegetative canopies and because of canopy effects on rates of transport and diffusion of such airborne materials as dust or smoke that, in turn, limit battleground visibility.

2. Because of these varied interests, considerable effort has been devoted to the characterization and quantification of plant canopy structure. However, these efforts have proceeded more or less independently within broad disciplinary lines; interdisciplinary exchanges of structural information and measurement techniques have been limited. This, coupled with the difficulty of measuring canopy structure, has impeded the development of an understanding of canopy structure and of its interactions with biological and environmental processes.

3. Interdisciplinary discussion of the problem of canopy structure characterization and quantification is needed to define current measurement and characterization capabilities, to stimulate information exchange between related areas of expertise, and to identify gaps in and limitations of current knowledge. To meet these needs, a workshop was held in April 1981, in Oak Ridge, Tennessee. The objectives of this workshop were to:

- a. Provide a forum for interdisciplinary communication.
- b. Identify a constituency for plant canopy structure information.
- c. Define needs for and applications of quantitative canopy structure information.
- d. Assess the state of the art of canopy structure measurement techniques.
- e. Define and assess needs for further research.
- f. Stimulate and focus new research efforts.

4. To satisfy the above objectives, a workshop agenda was formulated (see Appendix A) that would address the following questions:

- a. What is canopy structure?
- b. How can canopy structure be measured?
- c. What is the importance of canopy structure to various applications?
- d. What structural variables are important, and how accurately can and must they be quantified?
- e. How variable is canopy structure in space and in time, and what are the implications of this variability in terms of quantitative descriptions of canopy structure?
- f. What measurement techniques can be developed to effectively sample important structural variables?

5. To meet Objective a, the invitees to the workshop were scientists who not only worked with canopy structure, but who also represented a variety of scientific disciplines and geographic locations (see Appendix B). In addition, the workshop was structured so that group and individual discussions were stimulated (see Appendix A). The convening of this workshop will, it is hoped, satisfy Objective b. Objectives c, d, and e were specifically addressed in detail at the workshop. Finally, in addition to satisfying the terms of the contract with the Army Research Office for sponsoring this workshop, this summary will partially satisfy Objective f. On the basis of the enthusiastic participation of workshop participants, we are confident of continuing progress toward realization of these objectives.

PART II: WHAT IS CANOPY STRUCTURE?

6. Anyone who has ever walked from pavement onto turf on a hot day realizes that these two "surfaces" respond differently to identical insolation environments. These different responses are due to differences in energy and mass exchanges between the "surface" and the atmosphere that result from differences in the physical structure of the "surface" and from the physiological functioning of the grass plants that make up a turf. An asphalt surface is solid, tends to have high absorptivities for both solar and thermal radiation, high thermal mass, and is smoother than turf. A turf canopy, on the other hand, is porous; has varying spectral absorptivities, reflectivities, and transmissivities; has negligible thermal mass; and aerodynamically rougher than pavement. Furthermore, transpiration of the grass causes an exchange of latent heat, altering further the energy balance of the turf "surface." The result is that the pavement converts radiant energy into sensible heat that, as its name implies, is sensed as warmth. Since sunlit pavement is usually dry, it can only exchange this heat energy with its environment by conduction, convection, and long-wave radiation emission with little or no latent heat flux. Consequently, sunlit paved surfaces become very warm.

7. In contrast, the turf canopy, being porous, has an enhanced effective surface area that tends to increase conductive heat exchange (since well-mixed air can circulate through the canopy). Because of the different radiative properties of the turf, less solar energy is absorbed (more is reflected) so that less energy is converted to sensible heat. Latent heat exchange via transpiration further reduces the amount of sensible heat created. Thus, grassy areas have lower sunlit surface temperatures than pavements.

8. The various surface features that interact with physical phenomena to influence surface energy budgets are the structural variables that we wish to identify and quantify for stands of

vegetation. However, it is clear from this simplistic example that the definition of canopy structure varies according to the physical processes of interest. That is, the canopy structural features of importance to radiation exchange, for example, are not necessarily the same as those of importance to turbulent exchanges of materials across canopy-atmosphere interfaces or to canopy reflectance. In the midst of this complexity, only a simplistic definition seems generally applicable: canopy structure is the arrangement of aerial plant parts in space and time.

9. Fortunately, there is considerable overlap in the structural features of importance to a wide variety of phenomena, and many available measurement techniques provide general structural data that can be manipulated to discriminate process-specific variables. For example, most direct and indirect methods for determining biomass element amount and distribution can provide either three-dimensional or directional distributions of structural elements.

Structural Variables of Importance to Various Disciplines

10. Considerable discussion of canopy structural information needs in various broad scientific areas occurred. The scientific areas addressed included plant sciences and ecology, meteorology, and remote sensing and electro-magnetic interactions.

Canopy Structure Information Required in Plant Sciences and Ecology

11. In general, the structural information required for this area of science involves:

- a. Mean properties of the distribution of plant elements (foliage, twigs, etc.) within a canopy.

- b. Variability in gross spatial structure on the scales of individual shoots or branches, single plant crowns, and canopies of aggregated multiple-plant associations.
- c. Development (temporal variability) and morphology of individual plant crowns.

12. It is felt that the current state of mean, static canopy description is adequate for needs in this area of science. That is, present levels of knowledge regarding quantitative descriptions of canopy structure are not limiting the growth in our understanding of plant canopy functions in an average, static context. However, lack of information about the spatial variability in structural features within and among canopies is hindering development of knowledge of canopy processes. Additional canopy structure spatial information needs include:

- a. Variation within a given plant crown of stomatal properties, chemical properties, and anatomical features, including canopy element vestiture (i.e., hairiness, waxiness, etc.).
- b. Dispersion patterns of individual plant components within a crown.
- c. Dispersion of individual plant crowns within a stand canopy.

13. Knowledge of the magnitudes of spatial variations and of the spatial scales of those variations is lacking for virtually all canopy attributes. A good measure of the relevant scale for guiding sampling efforts is the most probable gap size associated with the plant units in question.

14. In contrast to description of static canopy properties, our ability to describe dynamic canopy structure development is weak. Research of the temporal variability of plant canopies is needed. With the development of remote sensing and indirect canopy assessment techniques, it appears that such efforts are now possible. In addition to basic studies of temporal changes in plant canopies, other

research is needed to broaden our understanding of the biological and physical ramifications of such temporal variation. Such research needs include:

- a. Incorporation of canopy development submodels based on first principles of plant physiology, anatomy, and biochemistry (especially as they relate to bud development) into canopy growth models.
- b. Investigation of the processes that control plant phenology and of how the phenological state of a plant canopy affects its structure. This includes time scales of a season, a plant lifetime, and, in the broadest sense of "ecosystem phenology," plant successional time.
- c. Studies of relationships between canopy structure and stand productivity in agriculture and forestry.

15. During the course of these discussions, the question of criteria for determining the importance of spatial patterns in canopy structure arose. A simple criterion for this determination was proposed (by H. Horn). If:

L = leaf area index (or plant element area index);

P_T = total canopy element projection, i.e., proportion of a horizontal surface beneath the canopy with no sky visible directly above;

P_h = foliage sample element projection onto horizontal surface; and

P_v = element projection onto vertical surface of same foliage sample,

then $\tan \alpha = \frac{P_v}{P_h}$ where α is the mean inclination of foliage elements.

Assuming that canopy elements are independently distributed and reasonably small, the total projected proportion of sky is

$$1 - P_T = \exp(-L \cos \alpha).$$

Introducing a variable c whose value depends on the degree of clumping of canopy elements and expanding $\cos \alpha$ in terms of P_v/P_h , this equation can be written

$$\ln (1 - P_T) = -c \left(\frac{1}{(P_v/P_h)^2 + 1} \right)^{\frac{1}{2}} L$$

While the value of c is unknown, its character can be determined from a plot of $\ln (1 - P_T)$ against L for replicated measurements of P_h and P_v . The nature of the resultant plot will indicate the importance of clumping. If the plot of $\ln (1 - P_T)$ against L is nonlinear, or if the plot is linear, but the value of c (the slope) is less than 1, a clumped distribution is indicated. Also, if $\cos \alpha \cong 1$, leaf inclination angles are unimportant, whereas if $\cos \alpha$ is less than 1, its value may help to identify the range of element inclination distributions of the stand.

16. Additional gaps in our knowledge of canopy structure involve:

- a. The factors allowing crown overlap in some canopies but not in others.
- b. The effects of plant social status (suppression, dominance) on crown architecture and physiological function.
- c. The effects of spatial patterning of canopy elements on heat, mass, and momentum transfer at the level of bulk exchange within the canopy as well as at the level of the arrangement of individual foliar elements on a shoot. The latter case will require detailed wind tunnel investigations of the effect of foliar display and geometry on the transfer of heat, mass, and momentum. The bulk exchange case is confounded by the distributed sources and sinks for heat, mass, and momentum in vegetation canopies. Solution of this problem will require experimental and theoretical studies of relationships between spatial distributions of canopy elements and source and sink strengths.

Finally, it was agreed that it is important to incorporate information on crown dimensions in any plant canopy measurement scheme.

Canopy Structure Information
of Importance to Meteorology

17. Studies of flow over canopies and of exchanges of momentum, heat, moisture, and other materials between vegetation and the lower atmosphere require either the direct measurement of fluxes or their estimation from other data. Although direct measurement is practical in some circumstances, such measurement is likely to remain a research tool available only to a limited fraction of the research community. It certainly will not become available on a routine basis at any more than a few sites. For modeling and for monitoring such as in hydrological studies, we must rely on fluxes inferred by other means. At this time, the relationships necessary for determining these quantities are quite uncertain. Thus, in recommending the kinds of canopy measurements most desirable from a meteorological viewpoint, we must focus on structural features that are known to enter into existing relationships between fluxes and mean meteorological quantities or that are known to impact the physical processes involved in surface-atmosphere exchanges and air-flow patterns in the lower atmosphere.

18. Above a canopy, relationships that are commonly accepted make use of gross aerodynamic canopy characteristics such as roughness length, displacement height, and surface temperature. These quantities are usually derived from more basic descriptors such as canopy depth and gross structural characteristics. The canopy structural features needed from a meteorological point of view are, therefore, those that will enable deduction of aerodynamic properties such as roughness length. In particular, the distributions of sources and sinks and of meteorological quantities within canopies are a subject of overriding concern that remains to be addressed in detail

before confidence in models purporting to relate canopy fluxes to bulk canopy structural and meteorological features can be generated.

19. Pollutant interactions with plant canopies are poorly understood but provide examples of special interest. For example, it is clear that sulfur dioxide and ozone uptake are substantially different. However, in daytime with dry foliage, net transfer rates of both will be governed by stomatal properties. When foliage is wet, SO_2 uptake will be enhanced because of its solubility whereas the uptake of insoluble ozone would be expected to be substantially reduced. For reasons such as these, canopy-element surface properties such as wetness or vestiture, especially waxiness, become important, despite the fact that contemporary models usually fail to recognize such factors as critical to uptake processes.

20. Applications in which in-canopy flow and dispersion become important require canopy structural characteristics of additional detail. Bulk descriptors of canopies, such as roughness length, are difficult to relate to in-canopy phenomena. Instead, we must be concerned with nonuniformities in canopy structure, with detailed descriptions of the drag characteristics of canopy elements and of their mutual interferences, and with detailed descriptions of biomass distributions. At present, models describing dispersion within canopies are in early stages of development, and good data bases are notably sparse. Creation of suitable data sets must be encouraged, not so much because models exist that require such data for testing, but because suitable models do not exist, and detailed sets of structural data are needed for model development. Consequently, any listing of structural variables of importance to meteorology will be weighted toward those features believed to influence in-canopy turbulence and dispersion. However, details of canopy interactions with structure turbulent dispersion are elusive and refractory. Therefore, such a listing constitutes only a considered opinion at this time.

21. These comments must be considered in terms of critical meteorological concerns regarding mesoscale features of canopies and of terrain as well. For example, a sloping site will be subject to subcanopy flows arising from cold air drainage. Such phenomena introduce flow and exchange characteristics that are likely to be site-specific. Information about structural effects on such phenomena must be obtained before models can be generalized.

Canopy Structure Requirements in Remote Sensing and
Electromagnetic Interactions Research and Application

22. From a remote sensing viewpoint, the structural features of a plant canopy of importance depend greatly on the application. For example, the structural features critical to an understanding of canopy controls on reflectance may be different from those features that may serve as carriers of information regarding biophysical attributes, e.g., total biomass, or condition states such as moisture stress. The structural features of importance may also vary with electromagnetic radiation wavelength or other phenomena, e.g., reflective and thermal radiation regimes, canopy effects on polarized radiation, microwave radiation interactions with canopies, etc. Furthermore, the spatial scale of the application strongly affects the kinds of structural information required.

23. In most respects, the canopy structure information needed for studies of remote sensing and electromagnetic radiation interactions is similar to that required for studies in the plant sciences. Abilities to characterize static canopy conditions are not generally limiting. (Structural properties important to plant canopy and microwave energy interactions are an important exception.) However, abilities to quantify complex terrain elements in space and in time are limiting progress in this area of science. Methods of identifying and quantifying nonrandomly mixed multicomponent, highly structured, and dynamic (e.g., heliotropic) terrain features are lacking as are

techniques for treating discontinuities (e.g., edges) in vegetative cover.

Identification of Canopy Structural Features

24. To illustrate what is meant by canopy structure and to demonstrate that considerable commonality exists in the structural details of importance to these three broad scientific areas, Table 1 has been synthesized from the workshop discussions. Identification of canopy structural features of importance was fairly easily accomplished. However, the problems of defining spatial and temporal variability and their relevant scales were less easily resolved.

Plant Canopy Spatial and Temporal Variabilities and Their Scales of Variation

25. Crown structure varies from plant to plant, while canopy structure varies from stand to stand. Within individual plants, elements making up the crown usually vary, at least in height. Superimposed on these space variations in structure are temporal changes ranging from leaf flutter (because of wind) to gross, long-term changes in canopy character (as in ecological succession). This problem can be resolved into two components: (1) the identification of the variations important to the various scientific disciplines requiring canopy structure information and (2) the identification of the scales at which these variations become important.

26. Because of differing emphases in different areas of science, the kinds and scales of variation of importance may be different depending on disciplinary interest and on application. For example, plant sciences studies and process models generally approach vegetative stands as an assembly of individual plants, i.e., stand responses are inferred as the integral of the responses of all the individual plants making up the stand. In remote sensing and meteorology, however, stand characteristics are usually inferred from stand or larger scale measurements, e.g., bulk canopy reflectance or

Table 1
Structural Features of Plant Canopies and Their
Applicability in Three Broad Scientific Areas

<u>Structural Feature</u>	<u>Scientific Area</u>		
	<u>Plant Sciences</u>	<u>Meteorology</u>	<u>Remote Sensing</u>
<u>Crown Element Descriptors</u>			
Plant Element Area Index (PAI) [Including leaf (LAI) and stem and branch (BAI) area indices]	X	X	X
Plant Element Inclination Angle Distribution	X	X	X
Plant Element Orientation Angle Distribution	X	X	X
Plant Element Spatial Density and Distribution	X	X	X
Plant Element Spectral Radiative Properties	X	X	X
Plant Element Surface Vestiture	X	X	X
Plant Element Surface Wetness	X	X	X
Plant Element Moisture Stress	X	X	X
Foliage Element Stomatal Resistance Distribution	X	X	X
<u>Descriptors of Canopy Element Assemblages</u>			
Branch or Shoot Density and Distribution	X	X	X

Table 1 (Concluded)

<u>Structural Feature</u>	<u>Scientific Area</u>		
	<u>Plant Sciences</u>	<u>Meteorology</u>	<u>Remote Sensing</u>
Bulk Shoot Spectral Radiative Properties	X	X	X
<u>Crown Descriptors</u>			
Gross Crown Morphology (Size and shape)	X	X	X
Bulk Crown Spectral Radiative Properties	X	X	X
Plant Silhouette (Outline) Area Distribution With Height		X	
Plant Crown Aeroelasticity		X	
Plant Biomass Thermal Storage	X	X	X
<u>Canopy Descriptors</u>			
Plant Height Distribution	X	X	
Canopy Closure-Gap Size Frequency Distribution	X	X	X
Density of Crowns in Canopy	X	X	X
Plant Species - Crown Morphology Distribution	X	X	X
Bulk Canopy Spectral Radiative Properties	X	X	X
Canopy Aeroelasticity		X	
Stand Biomass Thermal Storage	X	X	X

roughness length. However, while such larger scale bulk properties can be inferred from gross empirical measurements, real understanding of the physics of the processes will require much more detailed knowledge of canopy structure.

27. Considerable discussion evolved around the classification of scales of variabilities. Tables 2 and 3 present definitions of scales of spatial and temporal variabilities that were found useful in workshop discussions.

28. The point made above regarding the necessity for detailed canopy structural knowledge in the development of understanding of canopy-environment interactions must be emphasized here. Realistic modeling of these interactions at any particular scale requires knowledge of the structural features (or an ability to accurately parameterize them) at all smaller scales in space and in time. While the practical implications of this fact are awesome, continued disregard of this fact is scientifically indefensible.

Table 2
Scales of Plant Canopy Structure Spatial Variability

	n	Structural Properties of Various Scales
Sample Dimension (10^n m, $n = 0, 1, \dots, 4$)	0	Intracanopy Scale (Crown morphology, e.g., PAI, within crown spatial distribution and volume density of crown elements, inclination angle and azimuthal orientation distributions, element characteristics)
	1	Intercanopy Scale (Canopy structure, i.e., variability induced in above properties by arrangements of plants, species, or ages of plants in multiple association, arrangement of plant crowns in stand canopy)
	2	Microscale (Stand canopy structure within vegetation types, i.e., variability induced in above properties by arrangement of stands within a vegetation type)
	3	Mesoscale (Vegetation type canopy structure, i.e., variations induced by the mix of vegetative types and land use patterns)
	4	Macroscale (Regional and biome canopy features)

Table 3
Scales of Temporal Variability in Plant Canopy Structure

Time	Examples of Variations
Minutes	Wind Effects, e.g., Leaf Flutter, Crown Streamlining, etc.
Days	Effects of Plant Growth and Epinastic Phenomena
Seasons	Effects of Phenological Phenomena
Years	Effects of Perennial Plant Stand Growth and Changing Land Use Patterns
Decades & Longer	Effects of Ecological Succession and Long-Term Changes in Land Use Patterns

PART III: CANOPY STRUCTURE MEASUREMENT METHODS:
THE STATE OF THE ART

29. While plant physiologists, agronomists, and foresters recognized early on that canopy structure was heavily implicated in plant and stand growth and yield, definition and quantification of structural characteristics proceeded only slowly. Consider the following chronology:

- a. 1840 Mayer demonstrates that sunlight is energy source for photosynthetic process in green plants (Spoehr 1926).
- b. 1887 von Sachs addresses problem of interpretation of measurements of "light" in plant stands (von Sachs 1887).
- c. 1907 Weisner addresses effects of canopy geometry on "light" penetration into plant canopies (Weisner 1907).
- d. 1916 Clements introduces concept of ecological plant succession that explains significance of shade-tolerance (Clements 1916).
- e. 1932 Boysen-Jensen concludes that the attenuation of "light" in vegetation is a function of depth in the canopy (Boysen-Jensen 1932).
- f. 1944 Kittredge proposes a regression technique for estimating amounts of foliage in trees and in stands of trees (Kittredge 1944).
- g. 1947 Watson introduces the concept of leaf area index (Watson 1947).
- h. 1953 Monsi and Saeki hypothesize that attenuation of radiation in plant canopies is analogous to that in perfectly turbid media and introduce the "stratified-clip" method for direct, destructive measurement of canopy structure (Monsi and Saeki 1953).
- i. 1971 Horn addresses subject of the adaptive geometry of trees (Horn 1971).

- j. 1978 Hallé, Oldeman, and Tomlinson establish a detailed classification of models for crown architecture of tropical tree species (based on Hallé and Oldeman's 1970 book published in French) (Hallé et al. 1978).
- k. 1981 An English translation of an expanded version of Ross' 1973 summary of plant canopy architecture and radiation regimes (in Russian) is published (Ross 1981).

Reasons for this sluggish development are not entirely clear, but it seems likely that the spatial and temporal complexity of plant canopies combined with the temporal and labor intensiveness of direct measurements of canopy structure is involved. Recent advances in plant canopy radiation transfer theory combined with the development of mathematical inversion techniques promises at least partial resolution of this problem.

30. The state of the art of both direct (including destructive and nondestructive approaches) and indirect measurement techniques were reviewed at the workshop. Summaries of these reviews follow.

Direct Measurements of Canopy Structure

Destructive Techniques

31. Many destructive assessments of various aspects of plant and canopy structure have been made for a variety of reasons. Accuracy and precision of some forest sampling techniques, e.g., mean tree, regression, and statistical stratification methods, have been tested against complete harvest data (as in forest biomass surveys), but little study has apparently been made of the accuracy and application of such techniques in detailed assessments of canopy geometry.

In terms of merchantable or total forest biomass, existing techniques appear adequate for such determinations in even-aged, monospecific stands of vegetation. Their adequacy for use in uneven-aged, mixed species stands is somewhat doubtful, although Whittaker and Woodwell's (1968) studies in a Long Island oak-pine forest are reassuring. Destructive techniques are available for determinations of biomass and leaf areas in agricultural crops as well but, as in the case of larger vegetation, application of such techniques is tedious, and the information derived tends to be of limited applicability and is inadequate.

32. Whatever the capabilities of destructive assessments of stand canopy structure, the conclusion that this approach is far too demanding of labor and of time for most applications is inescapable. However, we may have to face the fact that some direct, destructive structural assessments will have to be made to test and fine-tune the newer indirect measurement schemes now coming on-line that hold such great promise for future work.

Nondestructive Techniques

33. A variety of nondestructive direct measurements approaches for canopy structural quantification and assessment have been devised and applied. These approaches involve the regression of structural characteristics, e.g., total biomass, LAI, or PAI, on some more easily measured quantity such as stem or branch diameter, or cross-sectional area of water-conducting tissues in plant branches or stems. Approaches relating canopy structure to amounts of water-conducting tissue have mostly been tried for woody trees and shrubs in which sapwood area is used as the independent variable. While these techniques require large amounts of time and labor for the development of the regression relationships, the approach provides highly accurate assessments of foliage biomass, for example, from a relatively few quick and simple measurements of branch or bole sapwood area.

Indirect Measurements of Canopy Structure

34. Indirect canopy structure measurements can and have been made from two different points of view: (1) looking down from above, e.g., ratios of selected spatial reflectances of plant canopies, inclined point quadrats, and (2) looking up from below the canopy, e.g., sunfleck analyses, hemispherical field-of-view photos of canopies, spatial coordinate surveys in tall vegetation. In general, the downward-looking approaches yield data containing less information about details of canopy structure than upward-looking ones. However, this limitation appears to have largely been avoided in the techniques recently proposed and tested by Donohoe (1981).

35. Downward-looking approaches include utilization of relationships between canopy structure and spectral reflectance ratios (e.g., Tucker 1979). Historically, such techniques proved effective only at low LAI (< 2), but more recent narrow band measurements have proven successful to LAI's of about 5 (Brach et al. 1981). Also included are potentially useful relationships among spectral bidirectional reflectance distribution functions (BRDF's), both specular and diffuse (along with, perhaps, information on the polarization of the specularly reflected radiation), and canopy structural features. Although these relationships are largely speculative at this time, it is felt that they are sufficiently well supported by theory to merit further study.

36. Another downward-looking approach is the inclined point quadrat technique devised largely by Wilson (1960, 1963, 1965), which utilizes the number of hits of an (theoretically) infinitely thin needle on vegetative elements as it passes through a canopy to derive estimates of LAI, PAI, and inclination angle distributions. The technique is capable of detailed assessments of these structural features, but it is very labor and time intensive and is difficult to

use in tall vegetation (> 1 or 2 m. height). Vanderbilt et al. (1979) have utilized the highly collimated light beam produced by a laser as the needle in their modification of the inclined point quadrat approach with considerable success in the determination of the structure of a wheat canopy. They report that with further automation of the laser approach, which is currently feasible, large data sets on canopy structure can be rapidly acquired.

37. Donohoe's (1981) approach is analogous to the upward-looking sunfleck analysis approach, but the sensor-source relationship is reversed, i.e., the radiation sensor is airborne, and radiation sources are located within the stand. Consequently, by varying the position of the airborne sensor, as by mounting it in an aircraft, the angular distribution of canopy gaps can be quickly and efficiently assessed. Since the position of the aircraft is controllable, such assessments are no longer dependent on the only slowly changing position of the sun as in conventional sunfleck analyses.

38. Upward-looking indirect canopy structure measurement techniques include photographic and sunfleck analyses and bidirectional transmittance distribution function (BTDF) measurement schemes.

39. There are many variations of the sunfleck analysis approach. Most assess gap frequency from hemispherical canopy photographs following techniques mostly devised by Anderson (1964). Some, e.g., Norman et al. (1971), perform the gap frequency analysis in the field (by measurement of sunlit fractions of horizontal transects through the stand), eliminating the photographic intermediate step. Conversion of such data to structural information requires a model to produce estimates of LAI and inclination angle distribution. Because the sunfleck analysis approach is sensitive to inhomogeneities in canopy structure, it appears that this approach will have greatest future utility in assessments of canopy inhomogeneities. Rather exotic analytical techniques have been applied to canopy photos [e.g., the laser diffraction technique of

Smith and Berry (1979)] to quantify specific structural features of canopies or of canopy element assemblages. The labor intensiveness and time demands for these approaches are variable. However, the sunfleck analyses and diffraction techniques have been demonstrated to provide quick and simple, highly accurate measures of certain structural features of plant canopies.

40. Vertically replicated measurements of BTDF's in crop and forest canopies have also been used to derive structural data. Although much work remains to be done, it appears that the BTDF becomes increasingly insensitive to LAI as LAI increases. Thus, the usefulness of this approach may be limited to plant stands having low LAI's or PAI's, as in winter deciduous forests.

41. Other structural assessment techniques have been devised and applied that do not fit nicely into an upward/downward-looking classification scheme. Among these approaches are several spatial survey techniques and an application of computer axial tomography (CAT) to the problem of canopy geometry assessment. West and Allen (1971) describe a theodolite survey technique for quantifying three-dimensional canopy structure that utilizes two theodolites and basic triangulation principles. Lang (1973) used potentiometric measurements of angles to determine the space coordinates of selected points in a cotton canopy in order to assess its geometry. Like the inclined point quadrat technique, these approaches are capable of detailed canopy structure assessments, but they are exceedingly labor intensive.

42. Vanderbilt and Kilgore (1981) have studied the applicability of CAT to the canopy structure measurement problem. They assumed that an optical CAT scanner could be constructed and conducted a proof-of-concept demonstration of the technique. They concluded that the approach shows promise for development of input data for canopy reflectance models.

43. Discussion of the applicability and capability of the various direct and indirect canopy structure assessment techniques led to the comparisons of Table 4.

Table 4
Canopy Structure Measurement Technique, Utility and Capability

Technique	Ease of Use	Ability to Discriminate		Canopy Element		Gap Probability	PAL (LAI)	PAL (LAI)	Reference
		Gross Morphology	Foliage Dispersion (Clumpiness)	Inclination Angle Distribution	Architectural Orientation Distribution				
Direct									
Destructive	Very tedious	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Monsi and Saeki 1953, Garry 1976
Nondestructive (Regression of structural characteristics on gross plant features)	Calibration tedious, simple to use Once Calibrated	No	No	No	No	No	Yes	Yes	Whittaker and Woodwell 1968, Grier and Marling 1974
Indirect									
Downward Looking									
Spectral Reflectance Ratios	Easy	No	Yes	No	No	Yes	Yes	Yes	Tucker 1979
BRDF	Easy but Unproven	Yes	?	?	?	Maybe	Yes (at low LAI)	?	Basic study remains to be performed
Point Quadrat	Tedious, Difficult	Small Scale-Yes Large Scale-No	Yes	Yes (but requires large amounts of data)	Yes (but requires large amounts of data)	Yes	Yes	Yes	Wilson 1960
Laser	Tedious, Difficult	Maybe	Yes	Yes (via model inversion)	Yes (via model inversion)	Maybe	Yes	Yes	Vanderbilt et al 1979
Airborne Radiometer/ In-Canopy Radiation Source	Easy	Yes	Yes	Yes (via model inversion)	No	Yes	Yes	Yes	Donohoe 1981
Upward Looking									
Hemispherical Canopy Photography	Tedious, Unless Automated	No	Yes	Yes (via model inversion)	Yes (via model inversion)	Yes	Yes	Yes	Anderson 1964
Sunfleck Analyses	Easy	No	Yes (via transect)	Yes (via model inversion)	No	Yes	Yes	Yes	Norman et al 1971
Optical Diffraction	Easy	Maybe	No	Yes	Maybe	No	No	No	Smith and Berry 1979
BRDF	Easy	No	No	Maybe	No	No	Yes	Yes	Norman and Jarvis 1975
Other									
Survey of Spatial Coordinates	Tedious	Yes	Yes	Yes	Yes	Yes	Yes	Yes	West and Allen 1971, Lang 1973
CAT	Potentially Easy but Untried	No	Yes	No	No	Yes	Yes	Yes	Vanderbilt and Kluge 1981

PART IV: RESEARCH NEEDS

44. As noted above, there was general satisfaction with present abilities of characterizing static canopy structure. Similarly, there was essentially unanimous agreement that abilities to measure and characterize the structural dynamics of canopies are lacking or, at least, are not fully developed. This lack is expressed, at the intra-canopy scale, as a need for:

- a. Incorporation of submodels based on first principles of plant physiology, anatomy, and biochemistry (especially as they relate to control of bud development) into canopy growth models.
- b. Investigation of the processes that control plant phenology and of how the phenological state of a plant canopy affects its structure. (This need spans time scales from one season to time involved in ecological plant succession.)
- c. Canopy-element (especially leaf) spectral reflectance properties and how these properties are affected by stress and other physiological conditions.

45. At intercanopy and larger scales, a basic need exists for models that synthesize information about canopy element properties and distributions into bulk crown and canopy properties. To further develop such synthesis models, studies of the spectral sensitivities of electromagnetic radiation to spatial and temporal inhomogeneities in canopy structure must be made so that realistic models and techniques for indirect assessments of larger scale canopy structure and its inhomogeneity can be developed.

PART V: RECOMMENDATIONS

46. Continued work is needed to (1) develop specific and useful definitions of plant canopy structure, (2) identify and quantify the role of the various aspects of structure in pertinent disciplines, (3) develop and test measurement techniques for each scale of canopy structure, (4) begin developing knowledge of the spatial and temporal variation of structure, and (5) use structure information in a wider range of development and applications projects. Workshop participants have identified a number of more specific recommendations that are mixed as to their levels of specificity and whether they represent near- or long-term goals. These can be summarized as follows:

- a. Define, by theoretical and experimental means, canopy structural characteristics involved in specific phenomena of interest and develop measurement techniques for quantifying those characteristics in real canopies.
- b. Test and compare canopy structure measurement techniques. Direct tests and comparisons are difficult because of the difficulty in obtaining "true" reference measurements and because of the variability of real-world canopy structure. Possibly a set of artificial standard canopies can be constructed, or a set of well-known and controlled vegetation plots could be established for use as reference standards.
- c. Encourage those involved in remote sensing to incorporate canopy structure measurements in their experimental plan. This recommendation applies, to a lesser extent, to all other disciplines in which canopy structure is involved.
- d. Develop experimental and theoretical techniques for determination of the effects of canopy structure and of changes in canopy structure on the fluxes of radiation and other quantities (e.g., CO_2 , water vapor, pollutants, momentum, etc.) through plant canopies.

- e. Continue to develop and quantify our understanding of the interrelationships between plant physiology/ecology and plant and canopy structure. Progress in this area will aid in defining canopy structure variability in space and time. Also, this will aid the understanding of the relationships between plant productivity and plant/canopy structure and may allow the development of improved planting practices and cultivar selection.

47. Finally, an awareness of the role of plant canopy structure in the various disciplines is limited to a small group of scientists. These scientists should be identified and brought together to foster interchange of ideas. Simultaneously, effort is needed to reach out and expand both the awareness and knowledge of the role of plant canopy structure to peers and to pertinent scientific and user communities. Hopefully, a larger total effort will result. Canopy structure studies will eventually need to be brought into the mainstream of research and development efforts for long-term progress.

PART VI: SUMMARY AND CONCLUSIONS

48. By design, participants in the workshop represented a wide cross section of disciplines and orientations involved with the understanding and use of plant canopy structure information. This diversity dominated workshop activities and defined the character and the strengths and weaknesses of the workshop. Diversity allowed for spirited and rich interactions among participants and a broadening of individual perspectives. These were helpful in satisfying objectives relating to interdisciplinary communication and constituency identification. However, the variety of viewpoints offered made it difficult to form consensus. Concise and general definitions of needs and applications for canopy structure information and the state of the art were not generated. Consensus was reached on some topics, but not on most. Thus, a process of building a body of knowledge was begun, and areas of confusion were identified. Progress toward the final objective, to stimulate and focus new research, must be evaluated at some time in the future.

49. Workshop participants were asked to address several questions during discussions. These questions and their best available answers are listed below.

50. What is canopy structure? Canopy structure elements discussed at the workshop ranged in size from leaf facets to the regional composition of vegetation communities and changed in time from a few minutes to many years. (Fortunately, time and space scales are often well correlated.) This range includes elements like leaf surface vestiture; arrangement of leaves on twigs; arrangement of branches, twigs, and leaves in a crown; arrangement of crowns in a stand; arrangement of stands in a region; and time variation of each. Given this large domain of canopy structure descriptions, a useful general definition is that canopy structure is the arrangement of plant parts

in space and time. Logically, more specific definitions are a subset of the general one. Operative concepts of canopy structure are highly problem-dependent, and no totally acceptable way of organizing them was found. Subdividing the domain of canopy structure descriptions with time and space scales was found to be useful for some specific applications, but a completely general classification was not developed. To the extent that canopy structure is defined by the way it is used, the reader is referred to Table 1.

51. How can canopy structure be measured? What measurement techniques can be developed to effectively sample important variables?

A tabular description of available measurement techniques is presented in Table 4. The possibility of using scanning airborne lasers or radars to determine crown height, shape, and/or distribution parameters as well as leaf angle and vertical distribution in conjunction with invertible models of radiant energy distribution of plant canopies was discussed.

52. What is the importance of canopy structure to various applications? Not much detailed attention was given to this question during the workshop. It seemed to be generally agreed that canopy structure has a pivotal role in dealing with processes in plant canopies. This probably results from the specialized nature of the group and may be self-evident. The importance of structure information is problem-dependent and often difficult to assess.

53. What structural variables are important, and how accurately must they be quantified? Again, a tabular presentation of important variables is given in Table 1. The best-developed theories tend to treat the canopies very simply: they assume horizontally homogeneous canopies and often describe structure with the vertical distribution of leaf area and, perhaps, a leaf inclination angle distribution. Mean leaf angle is probably an adequate substitute for leaf angle distribution at this time because of the general level at which processes are treated. Otherwise, an assessment of how accurately canopy structure variables should be quantified is still

needed. As the various disciplines treat energy processes in greater detail, it is likely that more detailed and more accurate characterizations of canopy structure will be needed.

54. How variable is canopy structure in space and time, and what are the implications of this variability? Partly because of the wide range of canopy structure variables discussed, assessment of their variability was not obtained. Also, the basis for making such an assessment is not yet available. Issues related to the spatial and temporal variation of plant canopy structure were raised more often, by far, than for any other of the topics discussed. Variability of plant canopy structure was the major immediate concern to most researchers and probably presents the next major conceptual barrier to the development of theories incorporating canopy structure effects.

55. The strengths of the workshop lie in the interactions between researchers with differing interests and knowledge. These interactions were of great value to most participants. A large number and a large range of ways canopy structure information is used were identified. Given this diversity and an incomplete understanding of canopy structure, it is not surprising that a consensus on definitions, assessments of requirements, and description of the state of the art was not achieved. Hopefully, this workshop will prove to be a part of the process of developing a more complete understanding and treatment of plant canopy structure.

PART VII: LITERATURE CITED

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APPENDIX A: WORKSHOP AGENDA

Sunday, April 26:

8:00 - 10:00 p.m.

Registration and Social
(Science Applications, Inc., Conference
Center)

Monday, April 27:

8:30 a.m.

Welcome and introduction to canopy structure workshop

9:00 a.m.

Canopy structure from a biological point of view

H. Horn, Princeton University

9:30 a.m.

Discussion

10:00 a.m.

Coffee

10:30 a.m.

Destructive techniques for canopy structure quantification

**B. Hutchison, Atmospheric Turbulence and
Diffusion Laboratory**

11:00 a.m.

Discussion

11:30 a.m.

Lunch

12:30 p.m.

Nondestructive techniques for canopy structure quantification

(1) Direct measurements

P. Jarvis, University of Edinburgh

1:00 p.m.

Discussion

1:15 p.m.

(2) Indirect measurements

J. Norman, University of Nebraska

1:45 p.m.

Discussion

Monday, April 27 (continued):

2:00 p.m.	(3) Scales of measurements and sampling problems L. Balick, Colorado State University
2:30 p.m.	Discussion
2:45 p.m.	Coffee
3:00 p.m.	Preparation of statement of the state of the art in quantification of canopy structure and of recommendations for further study
5:30 p.m.	Adjourn

Tuesday, April 28:

8:30 a.m.	Applications and needs for canopy structure information in: (a) Plant sciences Gaylon Campbell, Washington State University
9:00 a.m.	Discussion
9:15 a.m.	(b) Micrometeorology J. Bergen, Pacific Southwest Forest and Range Experiment Station
9:45 a.m.	Discussion
10:00 a.m.	Coffee
10:30 a.m.	Applications and needs in remote sensing and in electromagnetic interactions J. Smith, Colorado State University
11:00 a.m.	Discussion
11:30 a.m.	Lunch
12:30 p.m.	Information descriptions of canopy structure research (Poster Session)

Tuesday, April 28 (continued):

- 2:00 p.m. Concurrent working group discussions and report preparation on:
- (a) Canopy structure needs in ecology and plant sciences
G. Lovett, Dartmouth College, Chairman
 - (b) Canopy structure needs in meteorology
R. Cionco, Atmospheric Sciences Lab, Chairman
 - (c) Canopy structure in remote sensing and electromagnetic interactions
A. Strahler, University of California, Chairman
- 4:30 p.m. Plenary sessions for summarization of working group reports and discussions
- 5:30 p.m. Adjourn
- 7:30 p.m. Preparation of final report on needs for quantitative plant canopy structure information

Wednesday, April 29:

- 8:30 a.m. Concurrent working group discussions and development of plans for follow-up efforts:
- (a) Direct measurement techniques and validation
 - (b) Indirect measurement techniques and validation
 - (c) Mathematical characterization
- 12:00 p.m. Lunch
- 1:00 p.m. Final plenary session: Summarization of working group reports and discussion
- 3:00 p.m. Optional tour of Oak Ridge National Laboratory

Thursday, April 30:

Optional tour of the Atmospheric Turbulence and Diffusion Laboratory
Forest Meteorology Research Facility and demonstration of canopy
structure measurement techniques.

APPENDIX B: ATTENDEES OF WORKSHOP ON PLANT CANOPY STRUCTURE

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Lee K. Balick (Department of Forest and Wood
Science, Colorado State University) and Boyd A.
Hutchison (Atmospheric Turbulence and Diffusion
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